LIKELIHOOD-BASED GEOLOCATION PREDICTION ALGORITHMS FOR CDMA SYSTEMS USING PILOT STRENGTH MEASUREMENTS

Cross Reference To Related Applications

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This application is related to U.S. Serial No. 09/139,107 entitled "Pattern Recognition-Based Geolocation", filed in the names of T.C. Chiang et al on August 26, 1998; U.S. Serial No. 09/294,997 entitled "A Bayesian-Update Based Location Prediction Method For CDMA Systems", filed in the names of K.K. Chang et al on April 20, 1999; and U.S. Serial No. _________, (Lucent file #CHANG 4-2-16) entitled "Geolocation Estimation Method For CDMA Terminals Based On Pilot Strength Measurements", filed in the names of K.K. CHANG et al on May 28, 1999. These related applications are assigned to the assignee of the present invention and are meant to be incorporated herein by reference.

Background Of The Invention

Field of the Invention

The present invention relates to a method of locating a mobile telephone unit within a cellular service area, and more particularly to a method of predicting the location of a CDMA mobile unit based upon the probability of its being at a particular location of the service area using an algorithm providing a likelihood estimation of the mobile unit's location in response to a sequential set of attributes observed by the mobile unit and reported back to a base station.

Description of Related Art

A cellular telephone system must be able to locate a mobile unit within a cellular service area under various RF propagation conditions such, for example, when an E911 call is made from the mobile unit. Conventional methods for locating a mobile unit are typically based on either a triangulation technique which requires signals from three or more base stations within a designated service area, or an angle of arrival technique which requires at least two base stations. In many areas, the number of base stations the mobile unit can detect is less than two. Furthermore, both the triangulation and angle of arrival techniques inherently suffer from inaccuracies and signal fading which result from multi-path propagation.

In the first above-noted related patent application U.S. Serial No. 09/139,107 entitled "Pattern Recognition-Based Geolocation", RF characteristics pertaining to one or more pilot signals radiated from a base station and specific to a particular location within the service area are detected by a mobile unit and transmitted back to a base station where they are matched to a known set of RF characteristics and other information obtained from making attribute information measurements at all the grid points (sub-cells) in a cellular service area and which are then stored in a database located, for example, in a base station server.

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In the second above-noted related patent application U.S. Serial No. 09/294997 entitled "A Bayesian-Update Based Location Prediction Method For CDMA systems", the invention is directed to a method of estimating, by a Bayesian probability algorithm, the location of a mobile unit in the service area of a CDMA cellular telephone system using a model based approach which, among other things, simplifies the generation of a database containing a pilot signal visibility probabilities. This eliminates the need for repeated attribute measurements at all of the grid points in the service area.

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In the third above-noted related patent application U.S. Serial No. __________, entitled "Geolocation Estimation Method For CDMA Terminals Based On Pilot Strength Measurements", the invention is directed to a method of estimating the location of a mobile unit in the service area of a CDMA cellular telephone system also using a model based approach, but which now eliminates the need for a stored database containing pilot signal visibility probabilities for all of the grid points or sub-cells in the cellular service area. The estimation procedure is based entirely on analytical results involving one or more key approximations derived, for example, from an integrated model of the wireless communications system, its RF environment, and attribute measurement.

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Summary

The subject invention is directed to predicting the location of a mobile wireless communication unit in the service area of a CDMA communications system utilizing two likelihood functions that define maximum likelihood estimators of the mobile unit's location, based on attribute measurements, such as but not limited to pilot signal strength, being made at the location of the mobile unit and reported back to a base station. One of the likelihood functions comprises a frequentist likelihood function and the other comprises a

Bayesian-modified likelihood function. The likelihood functions are based on the assumption that there is an RF model which provides the probability a mobile unit is able to detect one or more attributes associated with an arbitrary base station, given it is located at an arbitrary location within the service area. The frequentist likelihood assumes the RF model provides exact visibility probabilities. In contrast, the Bayesian-modified likelihood assumes the RF model only provides reasonable approximations to the true visibility probabilities, and uses the approximations to construct a Bayesian prior distribution for the true values. Each of the likelihoods can be used in an iterative fashion to produce a maximum likelihood estimator for the location of the mobile unit by determining the coordinates within the service area which maximize the respective likelihood function. Alternatively, or in addition to, each of the likelihoods can be incorporated into a sequential Bayesian procedure which outputs a posterior distribution for the location of the mobile unit.

Brief Description of the Drawings

Figure 1 is illustrative of a cellular service area divided into a plurality of cells;

Figure 2 is illustrative of the cells shown in Figure 1 being further divided into sub-cells;

Figure 3 is illustrative of an embodiment of the subject invention; and

Figure 4 including Figures 4A-4E comprise flow charts which are illustrative of the preferred methods of determining the locality of a mobile unit in accordance with the subject invention.

Detailed Description of the Invention

Referring now to the drawings and more particularly to Figure 1, the reference numeral 10 denotes a service area for a CDMA cellular telephone system partitioned into a plurality of contiguous cells $12_1,\ldots,12_n$. Figure 1 also depicts a plurality of base stations $14_1,\ldots,14_n$ located within the service area 10. Also, the service area 10 includes at least one mobile switching center (MSC) 16. Typically each of the base stations $14_1,\ldots,14_n$ has a sectorized antenna with a distinct pilot signal channel associated with each sector. Three sectored antennas are most common. Each sector of the antenna serves a corresponding sector of the associated cell. In Figure 1, all of the base stations

$14_1,\ldots,14_n$ have three sectors each. The three sectors associated with base stations 14_1, for example, are denoted by the symbols $15_{1,1}$, $15_{1,2}$ and $15_{1,3}$, respectively. A mobile unit 20 is shown in sector $15_{2,1}$.

Figure 2 is illustrative of the cells $12_1,\ldots,12_n$ being further divided into sub-cells 18 and which are represented by a grid formed by rectilinear grid lines 20 and 22. The reference numbers 1, 2, 3 ... 6 of Figure 2 represent individual sub-cells $18_1,\ldots,18_6$, respectively.

Turning attention now to Figure 3, shown thereat is a diagram broadly illustrative of the system architecture for determining the location of a mobile unit 20 within the service area 10 in accordance with the subject invention. The MSC 16 operates in conjunction with the plurality of base stations $14_1,\ldots,14_n$ and connects to the local telephone system, not shown. A server 22 including digital computer apparatus 23 and memory 24, for storing computation procedures, model parameters and system data, are typically located at the site of the MSC 16 for purposes which will now be explained.

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~~In the invention described in the first referenced related application Serial No. 09/139,107 entitled "Pattern Recognition-Based Geolocation," each sub-cell $18_1,\ldots,18_n$ of the service area 10 is identified by a set of observable characteristics which are referred to as attributes. Examples of attributes are pilot signal strengths (Ec/Io), phase-offsets, angles of arrival, and pilot round trip delays. The invention of Serial No. 09/139,107 includes a database which contains attribute information which differentiates one sub-cell 18 from another and is generated by making a repeated and exhaustive survey which involves taking repeated measurements at all the sub-cells $18_1,\ldots,18_n$ (Figure 2) of the service area 10.~~

During the operation phase, after the database has been set up and the location service has been deployed, the mobile unit 20 detects and measures attribute values from its actual location in sub-cell 18_i and reports them via a message, e.g., a pilot signal strength measurement message (PSMM), to the base station(s) $14_1,\ldots,14_n$ (Figure 3), which can be one or more of the base stations with which it is in communication. The base station(s) forward their respective reported measurements to the geolocation server

22. The digital computer apparatus 23 associated with the server 22 statistically compares the measured values with the known attribute values stored in the database (memory) 24 of all the sub-cells 18 in the service area 10. The sub-cell 18_i whose attribute values as stored in the database provide the best match for the measurements reported by the mobile unit 20 is considered to be the best estimate of the mobile unit's location.

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~~In the second referenced related application, Serial No. 09/294,997, entitled "A Bayesian-Update Based Location Prediction Method For CDMA systems", a database is also used to assist the process of location estimation. However, in contrast to the first referenced patent application, i.e. Serial No. 09/139,107, it uses a model based approach to generate a database containing pilot visibility probabilities for different sub-cells 18 in the service area 10. The model-based approach requires that a limited number of pilot strength measurements be carried out along a few representative routes in the service area 10. These measurements are then used to identify the parameters of the model that characterizes the service area and its RF environment. Once these parameters are identified, simulations are then carried out to populate the database containing the pilot visibility probabilities, which are used in the computation of the location distribution of a mobile unit requesting location service. An iterative procedure based on a Bayesian probability computation is then used to obtain improved estimates of the mobile unit's location in response to multiple sets of attribute measurements being reported by the mobile unit 20. The model-based approach eliminates the need to carry out extensive measurements required by the first named invention, Serial No. 09/139,107.~~

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~~In the third referenced related patent application Serial No. __________, entitled "Geolocation Estimation Method For CDMA Terminals Based On Pilot Strength Measurements", the model-based approach embodied in Serial No. 09/294,997, "A Bayesian-Update Based Location Prediction Method...." to characterize the RF environment is used, as is the iterative procedure for computing the Bayesian posterior distribution for the location of the mobile. However, the database containing pilot visibility probabilities is replaced by analytical formulas that can be evaluated in real~~

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time. The evaluation procedures are compact and can typically be evaluated in the digital computer apparatus 23 shown in Figure 3.

Considering the present invention, the analytic formulation for the pilot visibility probabilities taught in the third referenced application Serial No.___________, "Geolocation Estimation Method For CDMA terminals Based On Pilot Strength Measurements", now serve as the starting point for the derivation of two likelihood functions, hereafter referred to as the frequentist and Bayes-modified likelihood functions, respectively.

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Each of the likelihood functions is derived based on the assumptions and mathematical formulations described in attached Appendix A. In as much as the likelihood functions depend on the analytic evaluation of the pilot visibility probabilities, attached Appendix B provides a self-contained development of the relevant details of these formulas. Each likelihood function is a function of (x, y), an arbitrary location of the mobile unit 20. Accordingly, each likelihood function could be used to obtain a maximum likelihood (ML) estimator of the location of the mobile unit 20 by finding the (x, y) which maximizes the value of the respective likelihood function. An iterative technique for sequentially updating each ML estimator with additional pilot signal strength measurements can be utilized. Each of the two likelihood functions can also be incorporated into a sequential Bayesian procedure, which outputs a posterior distribution for the location of the mobile.

The Bayes-modified likelihood function, whether it is used in the context of ML estimation or a sequential Bayesian procedure, is a substantial deviation from the inventions disclosed in the second and third above referenced related applications in the following way. Both of these previously disclosed inventions use an RF model to estimate pilot visibility probabilities, the former via simulation techniques, the latter via analytical formula evaluation, and implicitly assume that the model holds precisely. The present invention, however, uses the same RF model only to determine the means of beta distributions that are used as Bayesian priors for the true (unknown) pilot visibility probabilities. A beta distribution is completely determined once its mean and variance have been specified. Subject to the fixed mean values, each of the beta distributions is fully specified by maximizing their variances. Maximizing the variance of the beta priors, subject to the specified mean values, is consistent with a non-informative (vague) prior specification.

A summary of the derivations which appear in Appendix A will now be given as prefatory remarks to the description of the overall mobile unit 20 location prediction process depicted in Figure 4. In the example shown in Figures 1 and 2, if the primary base station for the mobile unit 20 is 14_2, the region designated as 17 in Figures 1 and 2 is the set of feasible locations of the mobile unit 20, and will hereafter be referred to as the region A. Along with the region A, the set of all pilots K which are likely to be visible at some of the grid points 18 in the set A is defined.

For each $(x,y) \in A$, let $\theta_{ij}(x,y)$ denote the true probability that the mobile unit 20 is able to see the pilot in sector j of base station i when it is located at (x,y). From hereon, the notation ij will be used to exclusively reference pilots from the set K. Let $\tilde{\theta}_{ij}(x,y)$ denote an approximation of $\theta_{ij}(x,y)$ based on an RF model described in Appendix B. For each pilot ij, let μ_{ij}^s equal one or zero depending on whether the mobile unit 20 can see pilot ij at the s-th measurement epoch or not, respectively. The frequentist likelihood through the first s measurement epochs has the following recursive form, starting with the definition $L_{ML}^0(x,y) \equiv 1$:

$$L_{ML}^s(x,y) \propto L_{ML}^{s-1}(x,y) \prod_{ij \in K} [\tilde{\theta}_{ij}(x,y)]^{\mu_{ij}^s} [1-\tilde{\theta}_{ij}(x,y)]^{1-\mu_{ij}^s} \quad , \quad (x,y) \in A \tag{1}$$

For the Bayes-modified likelihood, the prior for $\theta_{ij}(x,y)$ is a beta distribution with parameters:

$$\alpha_{ij}(x,y) = \begin{cases} 1 & , if\ \tilde{\theta}_{ij}(x,y) \le 1/2 \\ \dfrac{\tilde{\theta}_{ij}(x,y)}{1-\tilde{\theta}_{ij}(x,y)} & , if\ \tilde{\theta}_{ij}(x,y) > 1/2 \end{cases} \tag{2}$$

$$\beta_{ij}(x,y) = \begin{cases} \dfrac{1-\tilde{\theta}_{ij}(x,y)}{\tilde{\theta}_{ij}(x,y)} & , if\ \tilde{\theta}_{ij}(x,y) \le 1/2 \\ 1 & , if\ \tilde{\theta}_{ij}(x,y) > 1/2 . \end{cases} \tag{3}$$

The Bayes-modified likelihood function through the first s measurement epochs has the following recursive form starting with the definition $L_{BML}^0(x,y) \equiv 1$ for all

$(x,y) \in A$:

$$L^{s}_{BML}(x,y) \propto L^{s-1}_{BML}(x,y) \prod_{ij \in K} \frac{[n^{s-1}_{ij} + \alpha_{ij}(x,y)]^{\mu^{s}_{ij}} [s-1-n^{s-1}_{ij} + \beta_{ij}(x,y)]^{1-\mu^{s}_{ij}}}{\alpha_{ij}(x,y) + \beta_{ij}(x,y) + s - 1} \quad ,(x,y) \in A \qquad (4)$$

where $n^{s-1}_{ij} = \sum_{k=1}^{s-1} \mu^{k}_{ij}$ is the number of times pilot ij was visible amongst the first s-1 measurement epochs.

Each of the likelihood functions (1) and (4) are functions of $(x,y) \in A$, an arbitrary possible location for the mobile unit 20. The ML estimator for the location of the mobile unit 20 is obtained by evaluating (1) for all $(x,y) \in A$ and selecting the values, say (x^{s}_{ML}, y^{s}_{ML}), which gives the largest value of (1). An updated ML estimate is produced at each measurement epoch. In a similar way, using function (4) rather than function (1) generates a sequence of Bayes-modified ML estimates, say $(x^{s}_{BML}, y^{s}_{BML})$.

Utilizing functions (1) or (4) with a Bayesian sequential procedure can generate an alternative sequence of predictions for the location of the mobile unit 20. In each case, the initial prior distribution for the location of the mobile unit 20 is assumed to be a discrete uniform distribution of the form:

$$P^{0}_{ML}(x,y) = P^{0}_{BML}(x,y) = \frac{1}{\|A\|} \quad , \quad (x,y) \in A \qquad (5)$$

where $\|A\|$ is the number of grid points $18_1, \ldots 18_n$ contained within A. The posterior distribution for the location of the mobile unit 20, through s measurement epochs, based on the frequentist likelihood function (1) is, up to a constant of proportionality:

$$P^{s}_{ML}(x,y) \propto P^{s-1}_{ML}(x,y) \prod_{ij \in K} [\tilde{\theta}_{ij}(x,y)]^{\mu^{s}_{ij}} [1-\tilde{\theta}_{ij}(x,y)]^{1-\mu^{s}_{ij}} \ , \ (x,y) \in A. \qquad (6)$$

Alternatively, the posterior distribution of the location of the mobile unit 20, through s measurement epochs, based on the Bayes-modified likelihood function (4) is, up to a constant of proportionality:

$$P^{s}_{BML}(x,y) \propto P^{s-1}_{BML}(x,y) \prod_{ij \in K} \frac{[n^{s-1}_{ij} + \alpha_{ij}(x,y)]^{\mu^{s}_{ij}} [s-1-n^{s-1}_{ij} + \beta_{ij}(x,y)]^{1-\mu^{s}_{ij}}}{\alpha_{ij}(x,y) + \beta_{ij}(x,y) + s - 1}, \ (x,y) \in A. \qquad (7)$$

A Bayesian sequence of predictions on where the mobile unit 20 is located follows from functions (6) or (7) by using the mean or mode of the posterior distribution obtained at each measurement epoch. When function (7) is used, the sequence of prediction involves two distinct prior distributions, beta and discrete uniform, and the methodology is referred to as doubly-Bayesian. This completes the summary of Appendix A.

A description of the mobile unit 20 location prediction process depicted in Figure 4 will now be given. Considered in light of the accompanying appendices A and B and referring to Figures 4A-4E, the location prediction process in accordance with the subject invention, as noted above, is implemented in software which resides in the computer apparatus 23 located at the geolocation server 22 (Figure 3).

The process, referred to hereinafter as the geolocation process, begins at step 30 (Figure 4A) where it is waiting for a new location request to arrive. The geolocation process continually checks for the arrival of a location request at step 32, and if no such request has arrived, it goes back to the waiting state (step 30). When a location service request arrives, the geolocation process identifies the domain of support, i.e., the set of feasible locations, for the mobile's location based on either the identity of the primary base station of the mobile unit or the identity of the strongest pilot signal reported by the mobile unit. This is indicated in step 34. Pilot signals will hereinafter be referred to simply as "pilots."

In the example shown in Figures 1 and 2, if the primary base station for the mobile unit is base station14_2, the region designated 17 in Figures 1 and 2 would be selected as the domain of support for the mobile's location and will be hereinafter referred to as the region A. Along with the region A, the geolocation process at step 34 also identifies the set of all pilots K which are likely to be visible at some of the gridpoints 18 in the region A. Next, in step 36 approximations for the conditional probability, conditioned on the mobile unit being at a location $(x,y) \in A$, that each pilot in K is visible to the mobile are computed using equation (B9) from Appendix B. At this point, two decisions external to the geolocation process must be made. The first decision (step 38) that must be made is which of the ML estimation or sequential Bayes estimation methods should be used. For each estimation procedure (ML or sequential Bayes) the second decision to be made is which type of likelihood, frequentist or Bayes-modified, should be used (steps 40 and 42). These two

decisions result in the four paths marked (2)-(5). Figures 4B-4E correspond to each of the four paths, only one of which would typically be used in any implementation of the geolocation process.

First, suppose path (2) of Figure 4A is chosen which represents the combination of the sequential Bayes estimation method and the frequentist likelihood function. This is shown in Figure 4B. There step 44 assigns a discrete uniform prior probability to all grid points 18 in the set A. The discrete uniform prior reflects the initial state of no information about the mobile unit's whereabouts, other than the fact that it resides in the region A. The frequentist likelihood function is initialized to unity and time is set to s=1. Step 46 then evaluates the frequentist likelihood based on the first set (s=1) of visibility measurements using expression (1) noted above. In step 48, the posterior distribution based on the first set of visibility measurements is evaluated using function (6). Expression (6) results in values that must be normalized so that when they are summed over all $(x, y) \in A$, the result will be unity. The posterior distribution gives the updated probability distribution for the location of the mobile unit 20. A prediction of the location for the mobile unit 20 is next obtained in step 50 by computing either the mean or mode of the posterior distribution obtained from step 48. The prediction obtained in step 50 corresponds to the first set of measurements (s=1). If no further measurements are expected, the geolocation process terminates, otherwise as shown in step 52 it proceeds to a waiting state (step 54) and stays there (via step 56) until another set of measurements is received. At that point, the geolocation process proceeds to step 58 and increments time up to s+1 before proceeding back to step 46 and looping once again through step 48 and step 50 which lead to an updated prediction for the location of the mobile unit 20. Eventually, no further measurements will be expected and the geolocation process will terminate at step 52.

Next, suppose path (3) of Figure 4A, which is depicted in Figure 4C, is chosen which represents the combination of the sequential Bayes estimation method and the Bayes-modified likelihood function. Step 60 directs the calculation, via equations (2) and (3), noted above, of the two parameters for the beta prior distribution that is used for the true unknown pilot visibility probabilities. Step 62 assigns a discrete uniform prior probability to all grid points 18 in the set A. The discrete uniform prior reflects the initial state of no

information about the mobile unit's whereabouts, other than the fact that it resides in the region A. The Bayes-modified likelihood function is initialized to unity and time is set to s=1. Step 64 then evaluates the Bayes-modified likelihood based on the first set (s=1) of visibility measurements using functional expression (4). In step 66, the posterior distribution based on the first set of visibility measurements is evaluated using equation (7). Equation (7) gives values that must be normalized so that when they are summed over all $(x,y) \in A$, the result will be unity. The posterior distribution gives the updated probability distribution for the location of the mobile unit 20. A prediction of the location for the mobile unit 20 is obtained in step 68 by computing either the mean or mode of the posterior distribution obtained from step 66. The prediction obtained in step 68 corresponds to the first set of measurements (s=1). If no further measurements are expected, the geolocation process terminates, otherwise as shown in step 70 it proceeds to a waiting state (step 72) and stays there (via step 74) until another set of measurements is received. At that point, the geolocation process proceeds to step 76 and increments time up to s+1 before proceeding back to step 64 and looping once again through step 66 and step 68 which lead to an updated prediction for the location of the mobile unit 20. Eventually, no further measurements will be expected and the geolocation process will terminate at step 70.

Next, suppose path (4) of Figure 4A is chosen which represents the combination of the ML estimation method and the Bayes-modified likelihood function. Path (4) is shown in Figure 4D where step 78 first directs the calculation, via equations (2) and (3), of the two parameters for the beta prior distributions that are used for the true unknown pilot visibility probabilities. Step 80 initializes the Bayes-modified likelihood function to unity and time is set to s=1. Step 82 then evaluates, for all $(x,y) \in A$, the Bayes-modified likelihood based on the first set (s=1) of visibility measurements using expression (4). In step 84, the value of $(x,y) \in A$ which gives the largest likelihood value is selected as the Bayes-modified maximum likelihood estimator of the mobile unit's location The estimate obtained in step 84 corresponds to the first set of measurements (s=1). If no further measurements are expected, the geolocation process terminates, otherwise as shown in step 86 it proceeds to a waiting state (step 88) and stays there (via step 90) until another set of measurements is received. At that point, the geolocation process proceeds to step 92 and increments time up

to s+1 before proceeding back to step 82 and step 84 which lead to an updated prediction for the location of the mobile unit 20. Eventually, no further measurements will be expected and the geolocation process will terminate at step 86.

Finally, suppose path (5) of Figure 4A and further shown in Figure 4E, is chosen which represents the combination of the ML estimation method and the frequentist likelihood function. As shown, step 94 initializes the frequentist likelihood function to unity and time is set to s=1. Step 96 then evaluates, for all $(x, y) \in A$, the frequentist likelihood based on the first set (s=1) of visibility measurements using functional expression (1). In step 98, the value of $(x, y) \in A$ which gives the largest likelihood value is selected as the maximum likelihood estimator of the mobile unit's location. The estimate obtained in step 98 corresponds to the first set of measurements (s=1). If no further measurements are expected, the geolocation process terminates, otherwise as shown in step 100 it proceeds to a waiting state (step 102) and stays there (via step 104) until another set of measurements is received. At that point, the geolocation process proceeds to step 106 and increments time up to s+1 before proceeding back to step 96 and step 98 which lead to an updated prediction for the location of the mobile unit 20. Eventually, no further measurements will be expected and the geolocation process will terminate at step 100.

Each of the iterative procedures described above with respect to paths (2)-(5), operates to provide an improved estimate of the location of the mobile unit 20 as more and more sets of pilot measurements are reported. Each of the procedures can be readily extended to include other measured quantities such as phase offsets by including those data in the respective likelihood formulations. Also, when desirable, the method of the present invention can be modified so that the actual signal strength of the visible pilots can be used rather than a binary representation of the fact that the pilots are or are not visible.

The foregoing description of the preferred embodiment has been presented to illustrate the invention without intent to be exhaustive or to limit the invention to the form disclosed. In applying the invention, modification and variations can made by those skilled in the pertaining art without departing from the scope and spirit of the invention. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.